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As described by the title the grant funds were used to support a project whose primary goal was the development of tunable coherent sources for the THz-FIR region of the spectrum. The THz or more generally the FIR extends from 0.3 x 1012 (0.3THz) to 30 x I0t2 (30THz) or alternatively from a wavelength of l mm down to a wavelength of 10 gm. It is a range of the spectrum that has been a long standing challenge. Microwave technology which has been extraordinarily successful at wavelengths longer than 1 mm and classical and quantum optical techniques which are extremely effective in the visible, near and mid infrared regions of the spectrum encounter fundamental challenges when extended (respectively) to longer or shorter wavelengths. Continued interest in "opening up" and exploiting the FIR region of the spectrum is based on the scientific questions which in part demand an access to the THz-FIR spectral range. These extend from atmospheric and biophysics to plasma physics and radio astronomy. Important technological applications also exist. Among the examples would be radar modeling, characterization of the response of near millimeter wave (NMMW) systems and the potential for short range high resolution radar. The immediate scientific and engineering goals of the project supported by the equipment grant provide a source that is tunable, narrow band and provides sufficient power for spectroscopic investigations. In the longer term a compact conveniently packaged sources and potential and requirements needed to reach higher power operation are of interest. The grating couples the beam with the electromagnetic field provides distributed feedback which reacts back on the beam and in turn leads to bunching of the beam. The density bunches produce the coherent operation.

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Final Report

Coherent Tunable THz-FIR Radiation Sources

prepared by

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Contents

Project Summary

As described by the title the grant funds were used to support a project whose primary goal was the development of tunable coherent sources for the THz-FIR region of the spectrum. The THz or more generally the FIR extends from 0.3 x 10^{12} (0.3THz) to 30 x 10^{12} (30THz) or alternatively from a wavelength of 1mm down to a wavelength of 10 μm. It is a range of the spectrum that has been a long standing challenge. Microwave technology which has been extraordinarily successful at wavelengths longer than 1 mm and classical and quantum optical techniques which are extremely effective in the visible, near and mid infrared regions of the spectrum encounter fundamental challenges when extended (respectively) to longer or shorter wavelengths. Continued interest in "opening up" and exploiting the FIR region of the spectrum is based on the scientific questions which in part demand an access to the THz-FIR spectral range. These extend from atmospheric and biophysics to plasma physics and radio astronomy. Important technological applications also exist. Among the examples would be radar modeling, characterization of the response of near millimeter wave (NMMW) systems and the potential for short range high resolution radar. The immediate scientific and engineering goals of the project supported by the equipment grant provide a source that is tunable, narrow band and provides sufficient power for spectroscopic investigations. In the longer term a compact conveniently packaged sources and potential and requirements needed to reach higher power operation are of interest. The approach to developing a source was based on the use of an electron beam and a diffraction grating. The grating couples the beam with the electromagnetic field provides distributed feedback which reacts back on the beam and in turn leads to bunching of the beam. The density bunches produce the coherent operation. Coherent operation was first demonstrated during the course of the project (PRL <u>80</u> 1998, 516).

The use of an electron beam as a primary component even if technically a success may carry potential negative connotations in some applications. The present project is unique in this regard however. The usual difficulties and systems engineering complexity associated with vacuum approaches is circumvented. The final form of the devices that will result may be truly characterized as "vacuum micro-electronic" sources.

The ultimate cathode in the source will be based on single tip field emitters which are capable of providing many hundreds of amperes/ cm^2 a level far above that used in a conventional microwave tube. Total current from a single tip is low but the brightness A/cm^2 - sr) is extremely large. In order to couple effectively to a diffraction grating and produce radiation in the THz-FIR region of the spectrum the beam voltage is high by the standards of microwave tubes but very modest by there electron laser standards. A few 10's of kV will suffice. Voltages in this range at tube current levels required can be provided by another rapidly developing technology the dc-dc high voltage convectors. voltage sources which can produce 10's of kV in packages at no more than 10's of cm^3 volume are a practical reality.

Integration of bright cathode and compact high voltage source technology with the diffraction grating resonator a low loss surface emitter provide the essential components of a unique source for the THz-FIR range.

In order to explore the potential of this technical approach the electron beam in a scanning electron microscope (SEM) has been used to drive a diffraction grating. The beam is focused and positioned over the grating using the SEM's original internal focusing and control systems. A grating is installed on a miniature 10 x 10 cm "optical bench" which is mounted on the microscope stage. Radiation is emitted form the grating in the normal direction. The device is in effect a micro "Smith-Purcell" free electron laser.

The SEM which provides the e-beam for this investigation is small but except in relative terms it would not be characterized as "compact". However it is the ideal research tool for this investigation. The SEM also still functions as originally intended and thus provides a further very useful diagnostic capability. In sum it is the ideal e-beam source for exploring the potential of vacuum micro electronic sources. A final engineered device would of course dispense with the microscope. Ultimately a very compact device will result.

The scientific progress on "proof of principle" by this grant is summarized in three technical appendices to this report.

Equipment Purchased

The original equipment request is included with this report as Appendix B. Although not identical the equipment finally purchased matches the original request in scope and proportion. Expenditures for infrared detectors and signal processing equipment were increased. This change was made possible because an alternative and better means of providing a second e-beam system was adopted. In the original proposal funds for the construction of the second e-beam system were requested. The most expensive single item was the electron gun (item 1 in appendix B). During the time between submission and award a second SEM became available which provided both a better and less expensive approach to developing a second system.

The actual expenditures are listed on Table 1. Excepting the departure mentioned above the types of expenditures match the original request. The grant provided a range of infrared detectors, spectrometers and optical components. Vacuum components provide the opportunity to explore the capability of brighter cathode structures and the e-beam focus control system improves the overall stability of the system.

Table 1 Equipment Purchased

Detectors	
IR Laboratories	$15,190.00
QMC Instruments	26,404.50
EgaG Judson	1,763.02
Oxford Instruments	1,717.60
	45,075.12
Signal Processing Equipment	
LeCroy Digital Oscilloscope	$17,848.66
Stanford Res. Syst. LIA	3,950.00
Stanford Res. Syst. Pre-Amp	2,014.49
	23,813.15
Infrared Spectrometers	
Acton Research	$3,925.91
Acton Research	2,005.00
4DT X-ray Det	209.60
Welch Allyn Inc.	588.54
	6,729.05
2nd Prototypes System (excluding vacuum)	
Green Mountain Syst.	$2,000.00
Green Mountain Syst.	500.00
Trumbull Nelson Inc.	1,459.15
Spellman high Voltage Inc.	5,344.32
Fisher Scientific	503.28
Specialty Metals	799.37
	10,606.12
Vacuum Components	
Leybold Herceus Inc.	$3,794.60
MKS Inc.	1,355.49
Leybold Herceus Inc.	200.56
Varian Inc.	506.50
Varian Inc.	80.60
Varian Inc.	173.76
	6,111.51
Optical Elements (Inc. wire grids)	
Meles Griot	166.07
Thok Laboratories Inc.	2,873.15
V-Focus Inc.	1766.04
QNG wire grid	3,867.00
Newport Inc.	749.62
Edmund Scientific	307.30
	9,729.18

E-beam Focus Control System	
Micron Electronics	4,771.01
Edmund Scientific	636.40
Digi Key Corp.	405.30
National Instruments Inc.	3,427.05
Micro Motor Inc.	619.69
	9,859.45
Shipping Costs	
PLX	511.00
FEDEX	816.06
Universal Thr	598.86
	1,925.92
Non capital equipment	7,024.50
Total	120,874.00

Appendix A: Publication where the work was supported in part by DOD-AF-DURIP contract F49620-97-1-0287

1. A Coherent Tunable FIR Source, J. H. Brownell, M. F. Kimmitt, J. C. Swartz and J. E. Walsh, Proceedings of Ninth International Symposium on Space Terahertz Technology, pp 537-542, March 17 - 19, 1998 Sponsored by NASA Office of Space Sciences, Organized by the Jet Propulsion Laboratory and the California Institute of Technology.

2. A New Far infrared (FIR) Source, J. E. Walsh, J. C. Swartz, J. H. Brownell and M. F. Kimmitt, Proceedings of 23rd International Conference on Infrared and Mm waves, p 338, T. J. Parker and S. R. P. Smith Eds. U. of Essex, Colchester, UK, ISBN 0-953383903.

3. A New Far Infrared Free Electron Laser, J. E. Walsh, J. H. Brownell, J. C. Swartz, J. Urata, M. F. Kimmitt, Nuclear Instruments and Methods in Physics Research - A 429 (1999) pp 457 - 461.

Copies of the publications are included.

A COHERENT, TUNABLE, FIR SOURCE

J.H. Brownell, M.F. Kimmitt, J.C. Swartz and J.E. Walsh
Department of Physics and Astronomy, Dartmouth College, Hanover, New Hampshire 03755-3528
(March 18, 1998)

A tunable coherent source which operates in the THz–FIR region of the spectrum has been developed. The device, termed a grating-coupled oscillator (GCO) uses the beam in a scanning electron microscope (SEM) and a diffraction grating placed in the e-beam's focal region to generate the radiation. Distributed feedback is provided by the grating itself and the e-beam is focused and positioned using the microscope's internal control system. A summary of operating characteristics of the present device and a survey of the scaling relations which will determine the spectral coverage is presented. Comments on what will be required in order to develop a very compact device are also included.

I. INTRODUCTION

The region of the electromagnetic spectrum which falls in the approximate band of wavelengths between 10 and 1000 μm, the so-called far-infrared (FIR) spectral region, is relatively devoid of tunable, coherent, radiation sources. Until quite recently, and relative to the range of options available at longer and shorter wavelengths, this assertion would be almost indisputable. However, the challenge presented by the lack of sources together with the existence of a broad range of interesting research puzzles and opportunities has led to a renewed interest in providing access to this spectral region. The present note deals with one promising approach to a means of producing tunable THz or FIR radiation.

The beam in a scanning electron microscope (SEM) and a diffraction grating mounted in the e-beam focal region has been used to produce coherent radiation [1] over a range of wavelengths that extends from approximately 250 μm out to 1000 μm. Termed a grating-coupled oscillator (GCO), the device is a new variation on an old theme.

Observation of radiation produced by electrons skimming over a diffraction grating was first reported by Smith and Purcell [2] in 1953. Even earlier, Salisbury had filed a patent application [3] on a device based on the coupling of moving electrons and a diffraction grating although Salisbury apparently did not conduct experiments until somewhat later [4]. Others [5–8] have also followed up on the early work.

The radiation mechanism described in reference [1], which has become associated with the authors' names, was essentially an incoherent or shot noise process. Individual rulings on the grating contributed coherently to the passage of a single electron but the contributions of each electron in the beam added incoherently. This was a consequence of the fact that in the early experiments, the focus was on short wavelengths, visible, and the size of the beam was large relative to the wavelength. The relative beam energy which is also a factor in the dimensionless coupling parameter was also low. A quantitative discussion of this point is presented further along in the manuscript.

Coherent radiation at mm [9–12] and sub-mm [13,14] wavelengths has been introduced in grating-coupled devices. Termed either Orotrons [9,11–14] or the Ledatron [10], these devices used gratings embedded in Fabry-Perot resonators and electron beam technology similar to that used in other microwave tubes to produce the radiation. The name Ledatron, introduced by Mizuno [10], was an acronym that was chosen in order to emphasize the dual nature of the surface modes and the importance of both the bound and radiative space harmonics in the coupling and emission process.

In the present device it is the distributed feedback on the grating itself that leads to bunching of the electron beam and the growth of coherent radiation. The beam voltages are modest (10-50 kV) but higher than those used in any but high-power tubes. Beam current density is high (100 A/cm^2 or greater), but the total currents are modest (100's μA). The "quality" of the electron beam, energy spread and emittance are critical factors. Thus, overall, the "brightness" of the beam is very high. The "open" nature of the resonator together with the extremely bright electron beam are the essential features of the device.

The remainder of the paper is divided as follows: A survey of device performance will be given in Section II and a summary of basic scaling relations that govern device operation is contained in Section III. These sections are followed by brief remarks on possible means by which very compact GCO devices might be realized, and by concluding remarks.

II. SURVEY OF EXPERIMENTAL RESULTS

Given the importance of beam quality and brightness, an SEM is the ideal device for exploring the potential of the GCO. The beam quality is excellent and the microscope's own focusing and transport elements may be used to shape and position the beam. The beam column of the SEM used in the present experiments is illustrated in Fig. 1. Electrons are emitted from a Tungsten "hairpin" cathode and focussed by a Wehnelt electrode and a series of magnetic lenses. The waist of the beam is placed at approximately the midpoint of the grating and at present the lower limit to the waist diameter is approximately 25 μm. This however is a machine-design imposed but not an absolute limit. The beam may also be swept either in and out along the grating normal or across the grating surface. This provides a convenient temporal reference modulation. Operation in fixed spot temporally pulsed mode is also an option.

The grating is placed on a miniature "optical bench" which is mounted on the microscope stage. At present the FIR optical system limits observation to the normal direction and the grating parameters are chosen to optimize normal emission. Designs that circumvent this limitation are under evaluation.

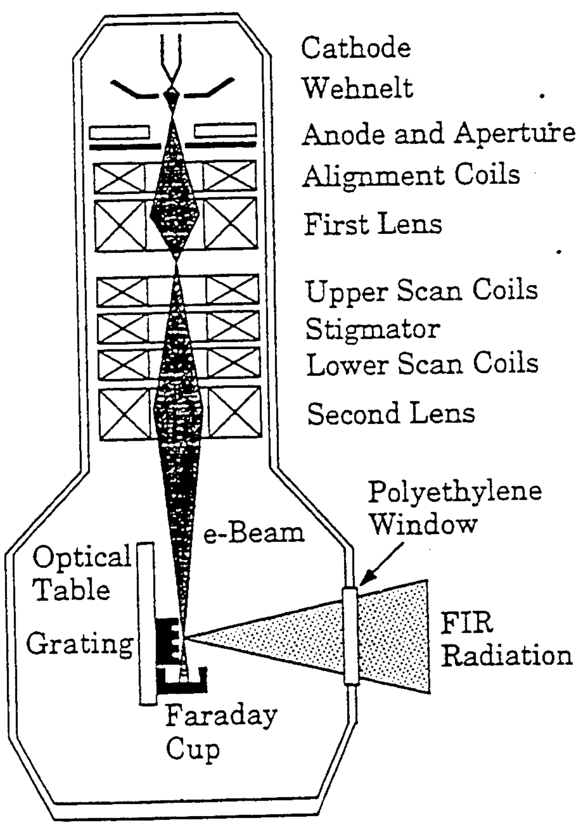

FIG. 1. Diagram of the SEM optical system.

A typical example of a plot of observed power versus electron beam current is shown in Fig. 2. It has two characteristic regions. When the current is relatively low and/or the beam diameter is comparatively large, the observed power increases linearly with current. This is characteristic of a shot noise or spontaneous emission process. In this region, a detailed analysis of the emission process has been carried out [15]. The emitted power in W/sr is given by:

$$\frac{dP}{d\Omega} = eI\frac{Nn^2}{2\ell\epsilon_0}F\left|R_n\right|^2\exp\left(-x_0/\lambda_e\right) \qquad (1)$$

where e is the electron charge, I is the beam current, N is the number of grating periods, n is the order of emission, ℓ is the grating period, and ϵ_0 is he permittivity of free space. Other parameter which appear in Eq. (1) are:

$$F = \frac{\sin^2\theta}{\left(1/\beta - \cos\theta\right)^3} \qquad (2)$$

$$\lambda_e = \frac{\gamma\beta\lambda}{4\pi} = \frac{\gamma\beta\ell}{4\pi|n|}\left(\frac{1}{\beta} - \cos\theta\right) \qquad (3)$$

Eq. (2) is the variation of the emission with polar angle. The symbols β and γ are respectively the electron velocity relative to the speed of light and the relative electron energy. Angles are measured with respect to the electron beam axis and x_0 is the distance of the infinitessimally thick beam above the grating. When observed power is composed with the prediction of Eq. (1), the measured beam profile is folded together with the evanescent field length given by Eq. (3). The remaining factor in Eq. (1), $|R_n|^2$, is in effect an antenna gain and the notation is that first introduced by van den Berg [16]. A detailed discussion that is adapted to the conditions of this experiment may be found in Urata [17].

When evaluated for parameters used in producing Fig. 2 and assuming an interaction length of 5 mm, Eq. (1) would predict emitted power levels of the order of 100 pW/μA-sr. The effective field of view of the collection optics is approximately 0.07 sr. The FIR emission is detected with a silicon composite bolometer placed between 0.5 and 1.0 m distant from the grating. Although the loss in the collection system is not accurately known, the theoretical predictions and estimated geometrical factors are consistent with the sub-nW power levels observed in the range where $P \propto I$.

The focused beam will support fast and slow space charge modes. As the beam plasma frequency is increased, those modes become resolved on the scale

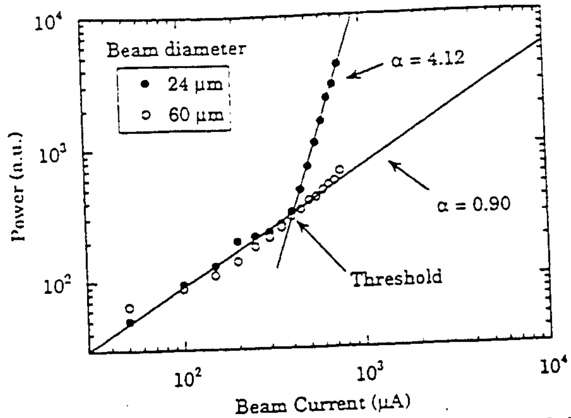

FIG. 2. Detected power vs. beam current. Fits of the form $y = Ax^{\alpha}$ are shown for the linear and superlinear regimes.

of the free spectral range which is determined by the beam velocity and the interaction length (i.e. the transit time). When, by increasing the beam current, this regime is reached, it is expected that coupling of the "negative energy" slow space charge wave with a co-propagating space harmonic component could result in a bunching of the beam. In this case, growth of the component of the emitted radiation will occur. While the details of the theory in this regime are still under development, such a transition is indeed observed. The transition occurs when the beam plasma frequency times the transit time exceeds 0.2-0.25. Beyond the transition point, the radiated power grows rapidly as a power of the current exceeding the expected spontaneous emission by 1 to 2 orders of magnitude. The exponent in this power law relation typically ranges from 3 to 6 and is sensitive to the operating conditions. With the present operating parameters, the system does not appear to have reached saturation.

It is clear that the finite length grating is functioning as a relatively high quality surface resonator but the details are yet to be understood. A similar caveat applies to the non-linear regime but Eq. (1) provides a basis for some interesting estimated. Since it is proportional to the product of the electron charge and the current, it has the characteristic form of a shot noise formula. If it is multiplied and divided by a spectral interval, $d\omega$, and the product eI factored out, what remains is a "radiation resistance". The spectral width of the spontaneous emission "Smith-Purcell line" has been deduced from both grating spectrometer and Fourier transform interferometer measurements. In either case the spectral width is about $\Delta\nu \approx 1\text{cm}^{-1}$. Converting this to an angular frequency, $d\omega$, and using a beam current of 100 μA, the factors

$$eId\omega = 3.2p\text{W}/\Omega \tag{4}$$

Thus the measured power near the upper limit of the spontaneous emission regime indicates that the radiation resistance lies between 1 and 10 kΩ. The interaction length and the exact value of the beam profile – evanescent wave overlap are not determined precisely. However the 1–10 kΩ range for a radiation resistance is also consistant with an independent evaluation of Eq. (1) (after factoring out eI and evaluating $d\Omega/d\omega$).

A bunched beam with 100 μA rms current would be expected to generate between 10 and 100 μW. A beam with approximately one order of magnitude greater current ($\approx$ 1 mA) would produce power levels in the mW range.

These arguments are qualitative but they are also based on fundamental constraints. The estimates probably represent reasonable upper limits to what can be expected from SEM electron optical system based e-beam technology.

III. SCALING OF GCO DESIGN CONSTRAINTS

A discussion of the constraints governing GCO operation is facilitated by first examining the dispersion plane associated with the electromagnetic fields above a grating. A schematic dispersion plane is illustrated in Fig. 3. The vertical axis is the angular frequency measured in units of 2π times the speed of light divided by the grating period. The horizontal axis is the wave number along the grating in a direction perpendicular to the rulings. Again, the units are normalized.

The plane is divided into two principal regions, "fast" and "slow". These designations are relative to

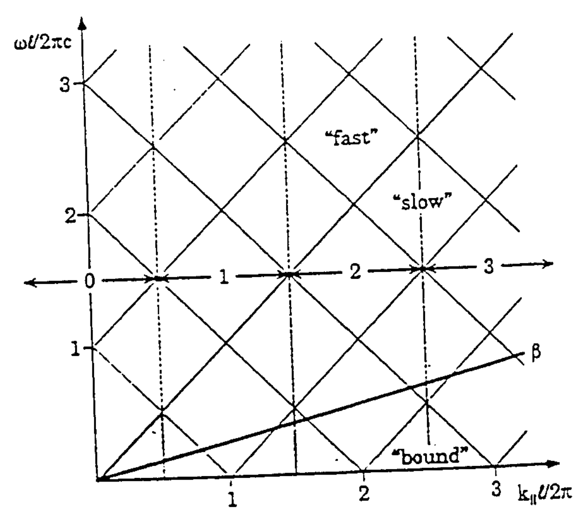

FIG. 3. Schematic of GCO dispersion plane.

the speed of light, the lines with slope ± 1 on the diagram. Each Fourier component of the field above the grating will contain a complete set of space harmonic whose axial wave numbers differ by $2\pi/\ell$. Space harmonics with phase velocities that fall within the "light cone", the region labeled fast, satisfy radiative boundary conditions. The points in the fast region represent components of either incident and scattered waves or an outgoing wave generated by the beam.

Points on the plane which fall outside the light cone have phase velocities less than the speed of light. Space harmonic components in this region are non-radiative but they do serve as a coupling mechanism for the electron beam. A "beam line" is also shown on the figure. Along this line the relation

$$\omega = k_{\|} v \tag{5}$$

is satisifed (ω is the angular frequency, $k_{\|}$ is the axial wave number in dimensional units, and v is the velocity of the beam. In the current discussion only waves which have at least one space harmonic component in this light cone are of interest. Thus, the darker shaded areas, marked bound, may be ignored. The wavenumber which appears in Eq. (5) may be broken down into two components

$$k_{\|} = k_0 + 2\pi|n|/\ell \tag{6}$$

where

$$k_0 = (\omega/c)\cos\theta \tag{7}$$

is the axial component of the wavenumber along the grating that would be associated with an outgoing radiative wave. Combining Eqs. (5 – 7) and choosing $|n| = 1$ yields

$$\frac{\omega}{c} = \frac{2\pi/\ell}{1/\beta - \cos\theta} \tag{8}$$

or

$$\lambda = \ell\,(1/\beta - \cos\theta) \tag{9}$$

which is the well-known relation discussed by Smith and Purcell in Ref. [2]. It can also be deduced using the Huygens construction.

The choice $|n| = 1$ is not necessarily the dominant mode. It is interesting to note that if, for instance, the depth of the grating is chosen in order to optimize the spontaneous emission for $|n| = 3$ that mode will also dominate above threshhold (Fig. 4). Small variations in voltage will also lead to $|n| = 1$ and $|n| = 3$ operating simultaneously (Figs. 5 and 6). The potential for operation on higher-order modes of the grating provides an important degree of freedom for grating design.

Another important constraint is related to the evanescent scale length of the slow space harmonics. Outside the light cone, the square of the perpendicular component of the total wavenumber is less than

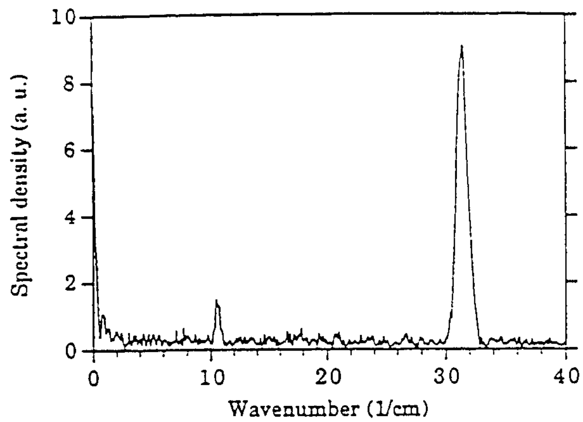

FIG. 4. Power spectrum of GCO operating at $|n| = 3$.

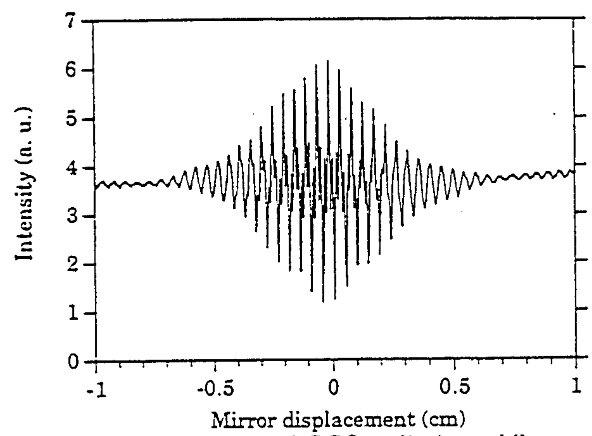

FIG. 5. Interferogram of GCO radiation while operating simultaneously at $|n| = 1$ and $|n| = 3$.

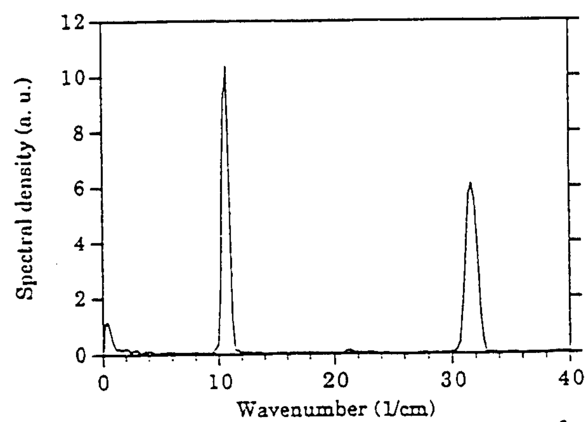

FIG. 6. Power spectrum inferred from the interferogram in Fig. 5.

zero and the wavenumber itself is pure imaginary and has a magnitude

$$|k_\perp| = \sqrt{k_\parallel^2 - \omega^2/c^2} \tag{10}$$

Since energy transfer is through the nearly-synchronous co-propagating space harmonic the relation $k_\parallel = \omega/v$ can be used to infer that

$$|k_\perp| = \omega/v\gamma \tag{11}$$

where $\gamma = 1/\sqrt{1-\beta^2}$. Thus,

$$|k_\perp| = 2\pi/\gamma\beta\lambda \tag{12}$$

or

$$|k_\perp|^{-1} = \lambda_e \tag{13}$$

the evanescent scale length introduced in Section II. In general, good coupling will require the beam diameter to be

$$d \leq \lambda_e \tag{14}$$

or

$$\lambda \geq 2\pi d/\gamma\beta \tag{15}$$

Using the values associated with a 25 kV beam gives the relation

$$\lambda \geq 20d \tag{16}$$

Good coupling at 300 μm (1 THz) would be achieved with a beam parameter of the order of 15 μm. This is consistent with data obtained in the proof-of-principle experiments. Experiments designed to test the lower limits of d are currently in progress. Much smaller values of d are achievable and operation well above 1 THz may be expected. Further extension of the evanescence scale length may also be achieved by increasing the beam voltage.

A final pair of scaling relations follow if it may be assumed that the depth of field of the beam focus is emittance dominated and that this limits the effective interaction length. In this case the interaction length L is related to the beam diameter by the expression

$$L \simeq \frac{\gamma\beta d^2}{\epsilon_N} \tag{17}$$

where ϵ_N is the normalized emittance. Since d and λ_e are comparable, the relation

$$L \simeq \frac{\gamma\beta\lambda_e^2}{\epsilon_N} \tag{18}$$

also follows.

Threshhold occurs when the beam plasma frequency ω_b times the transit time of a beam electron through the interaction length exceeds about 0.25. Operation well above threshhold will require

$$\frac{\omega_b L}{\gamma^{3/2} v} > 1 \tag{19}$$

(where the factor $\gamma^{3/2}$ has been included since the bunching is longitudinal; it has, of course, a negligible numerical effect for non-relativistic beams).

With the aid of the usual expression for the beam plasma frequency and multiplying and dividing by additional factor of beam velocity yields the constraint

$$\frac{JL^2}{(\epsilon_0 mc^3/e)(\gamma\beta)^3} > 1 \tag{20}$$

where J is the beam current density. If the relation between the interaction length and the evanescent scale are invoked, the constraint becomes

$$\frac{J\lambda_e^4}{(\epsilon_0 mc^3/e)\gamma\beta\epsilon_N^2} > 1 \tag{21}$$

Finally, if re-written in terms of wavelength, the result

$$\lambda > 2\pi\left[\frac{(\epsilon_0 mc^3/e)\epsilon_N^2}{(\gamma\beta)^3 J}\right]^{1/4} \tag{22}$$

is obtained. Evaluating this last expression using typical parameters for the present electron optical system indicates that we are operating near the lower wavelength limit of that apparatus.

IV. TOWARD A COMPACT GCO

The GCO described in the preceding sections is already compact by some standards. As is evident from the scaling relations discussed in Section III, increase of beam energy as well as a decrease of beam emittance can be used to lower the limiting wavelength. Increasing the beam energy is, of course, the route taken in relativistic electron-beam-driven, free-electron lasers (FEL). The present GCO is already far smaller than these devices. The GCO's output power is much smaller than the levels produced by a relativistic beam-driven FEL. However, it is already sufficient for application in spectroscopy or as a local oscillator.

Straightforward engineering and elimination of the non-essential features of the SEM would lead immediately to a much smaller device. It is also interesting to speculate on more dramatic options.

The beam voltage required for GCO operation probably need never exceed 50 kV and in the present device, THz operation is achieved with only 20 kV of beam voltage. This range is well within the scope of modern dc–dc converter-based power supply technology. The beam currents required are also modest and well within the scope of current converter-based power supplies. These supplies can now be obtained in very compact packages.

A second major reduction in size might be obtained if modern field emission cathode technology were employed. The primary motivation for much work on the field emission cathode is for use in flat panel displays. However, use in microwave tubes has also been a factor. The GCO is an ideal place to use this technique. A ribbon beam a micron thick and about a millimeter wide propagating a distance no more than a few centimeters would be ideal. Power consumption and heat load would be reduced dramatically.

The GCO is also a linear device and standard energy recovery technology is probably applicable. Implementation of energy recovery would improve terminal efficiency. If done in a way such as to also reduce beam intercept at high voltages the already-modest x-ray production could be further reduced.

Finally, although the grating is a simple and reliable means of converting electron beam kinetic energy to coherent radiation, other photonic band gap structures might be employed. The present GCO uses only the distributed feedback on the grating. More complex structures, particularly ones with well-defined high-quality factor modes, may offer significant advantages.

V. CONCLUSIONS

A potentially very useful THz-FIR source has been developed. Based on a novel variation of an old theme, the device is simple and versatile. Power output levels and tuning range are already of interest in some applications and fundamental scaling arguments support the claim that considerable extension of the tuning range and output power is possible. If operated near the limit of established electron beam optical art it will be possible to access the challenging 10-1000 μm wavelength range.

Support from ARO Contract DAAH04-95-1-0640, DoD/AF DURIP Contract F49620-97-1-0287, and Vermont Photonics, Inc., is gratefully acknowledged.

[1] J. Urata, M. Goldstein, M.F. Kimmitt, A. Naumov, C. Platt and J.E. Walsh, Phys. Rev. Lett. **80**, 516 (1998).

[2] S.J. Smith and E.M. Purcell, Phys. Rev. **92**, 1069 (1953).

[3] W.W. Salisbury, US Patent 2,634,372, filed October 26, 1949, granted April 7, 1953.

[4] J.P. Bachheimer, Phys.Rev. B **6**, 2985 (1972).

[5] W.W. Salisbury, Science **154**, 386 (1966).

[6] E.L. Burdette and G. Hughes, Phys. Rev. A **14**, 1766 (1976).

[7] A. Gover, P. Dvorkis and U. Elisha, J. Opt. Soc. Am. B **1**, 723 (1984).

[8] I. Shih, D.B. Chang, J.E. Drummond, K.L. Dubbs, D.L. Masters, R.M. Prohaska and W.W. Salisbury, J. Opt. Soc. Am. B **7**, 351 (1990).

[9] F.S. Rusin and G. Bogomolov, Proc. IEEE **57**, 720 (1969).

[10] K. Mizuno and S. Ono, The Ledatron, Infrared and Millimeter Waves 1: Sources of Radiation, ed. K. Button (Academic Press, Inc., 1979), Ch. 5, pp. 213-233.

[11] D.E. Wortman, H. Dropkin and R.P. Leavitt, IEEE Journ. Quant. Elect. QE-17(8), 1341 (1981).

[12] V.P. Shestapolov, Diffraction Electronics (Kharkhov: 1976).

[13] E.J. Price, Appl. Phys. Lett. **61**, 252 (1992).

[14] J.H. Killoran, IEEE Trans. Pl. Sci. **22**, 530 (1994).

[15] M. Goldstein, J.E. Walsh, M.F. Kimmitt, J. Urata and C.L. Platt, Appl. Phys. Lett. 71, 452 (1997) and A Far-Infrared Smith-Purcell Micro-Radiator, Ph.D. thesis, 1994, available from Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755.

[16] P.M. van den Berg, J. Opt. Soc. **63**, 1588 (1973).

[17] J. Urata, Spontaneous and Stimulated Smith-Purcell Radiation Experiments in the Far-Infrared, Ph.D. thesis, 1997, pp. 19-20, available from Department of Physics and Astronomy, Dartmouth College, Hanover, NH 03755.

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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A new far infrared free-electron laser

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Abstract

The operation of a new ultra compact diffraction grating coupled free-electron laser (FEL) has been demonstrated. The basic elements of the device which is termed a grating coupled oscillator (GCO) are the beam in a scanning electron microscope (SEM) and a diffraction grating which is mounted in the e-beam focal region of the SEM. The e-beam is controlled by the SEM's electron optical system and distributed feed back is provided by the grating itself. Recent experimental results are presented and techniques for extending the wavelength and power coverage are discussed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: SEM; Grating; Electrons

1. Introduction

Observations of radiation produced by electrons moving near the surface of a diffraction grating were first described by Smith and Purcell in 1953 [1] and suggestions that this radiative mechanism could be the basis of a useful radiation source were made even earlier [2]. Over the intervening near half-century, interest has been sustained. At visible and near visible wavelengths experiments similar to the one described in Ref. [1] were carried out by a number of researchers. In the millimeter range of the spectrum coherent sources [3–6] which used gratings as coupling elements, were developed. At short wavelengths (the visible and near infrared range) the limited brightness of the electron beams employed in the experiments limited the degree of coherence. However, this is not a fundamental constraint. Recently [7], the electron beam in a scanning electron microscope (SEM) and a diffraction grating mounted in the e-beam focal region have been used to produce coherent radiation at far infrared (FIR) wavelengths. The characteristics of this device will be described and conditions required for extension toward operation at shorter wavelengths will be discussed.

2. The SEM-based FEL

A schematic cross-section of the SEM-FEL is shown in Fig. 1. The beam is formed on a Tungsten "hairpin" cathode and it is focused and positioned over the grating with the SEM's internal electron optical system. When used as a microscope very small beam currents are typically employed. However, the present system is capable of running in the low milliamp range provided care is taken with heat sinking. This current level is more than sufficient for operating in the super radiant regime.

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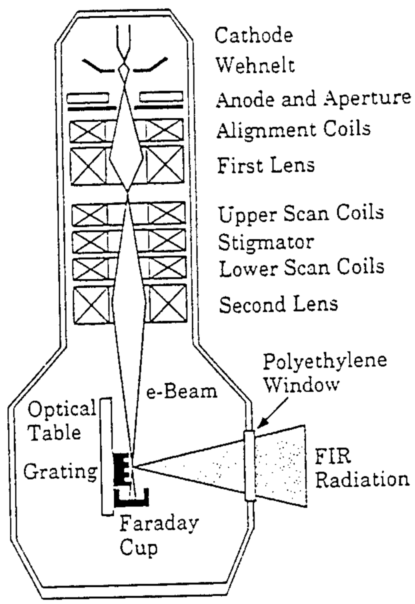

Fig. 1. Schematic diagram of the SEM-GCO.

Various short pulse schemes would yield still higher currents. The beam voltage may be varied up to 40 kV. Again this is a convenient limit for the present apparatus but not a fundamental constraint. Operation at 1.5 THz (200 μm wavelength) has been achieved with a 25 kV beam. Although run in a regime well above its intended design limit the SEM beam retains the tight focusing and high brightness that is characteristic of these devices. At present the smallest beam waist radius that can be easily attained is approximately 12 μm. This yields peak beam current densities in the 200 A/cm^2 range. The beam emittance can be measured in situ with either a 3-wire profilometer or knife edges. Normalized emittance values are typically in the range at $10^{-2}\pi$mm mrad, a range that is two orders of magnitude smaller than the standard high-quality RF linac. Thus although the current in the SEM is much lower than typical linac currents beam brightness may be comparable.

The gratings used in the present experiment are 2–4 mm wide and 10–15 mm long. The gratings are mounted on a miniature optical table that has been drilled with holes on $\frac{1}{4}''$ centers. Other components including Faraday cups and the profilometer are mounted on the table. The complete assembly is mounted on the microscope stage which brings flexibility to the task of precise alignment.

3. Experiments

The SEM in its original role as a microscope can be used to align the grating. Peak signal is obtained when the beam axis and grating surface are parallel. When the beam current is at the low end of its range and/or it is not tightly focused, signal power increases linearly with beam current. In this regime, coupling conditions are comparable to those encountered in the early experiments of Smith and Purcell. Energy is transferred to the radiation field via a velocity synchronous coupling of the beam electron and one of the slow space harmonic components of the field. Space harmonic components propagating at the same velocity as the beam electrons "evanesce" away from the surface with a characteristic scale length given by the expression

$$\lambda_e = \lambda\beta\gamma/2\pi$$

where λ is the operating wavelength and β and γ are the velocity of a beam electron relative to the speed of light and the relative energy. In order to couple efficiently λ_e must be comparable to the position of the beam centroid above the grating. In the experiments carried out by Smith and Purcell and in similar early work the beam diameter was much greater than λ_e. When this is the case the emission from individual electrons add incoherently and power increases linearly with beam current. This is the spontaneous emission or shot noise regime.

Each mode on the grating consists of a set of space harmonics. Space harmonic components with phase velocities which fall within the light cone on a dispersion plane produce the outgoing radiation. Space harmonic components which have velocities which fall outside of the light cone are trapped on the surface. In addition to providing beam-grating coupling these field components provide a distributed feed back. This is always the case but when the beam current density is sufficient the system enters a super linear regime. Output power then increases in proportion to a substantial power of the current.

The details of this super radiant operating regime are still under investigation but certain general

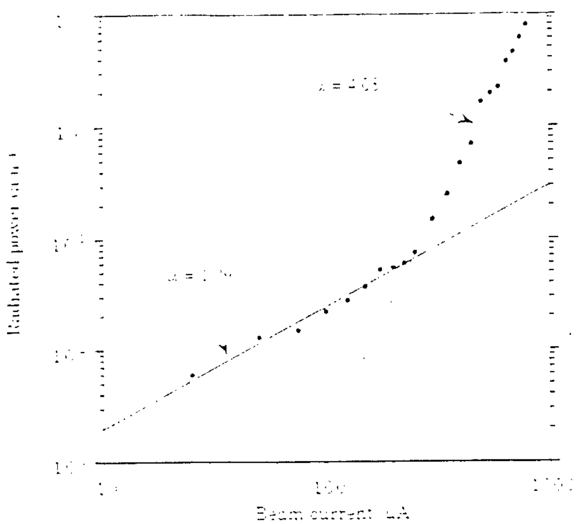

Fig. 2. Typical power versus beam current relation.

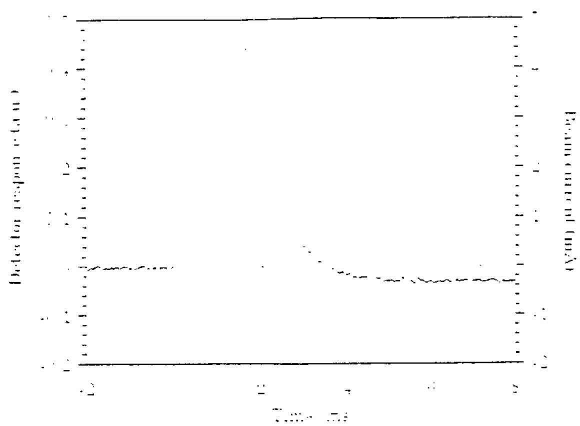

Fig. 3. A single unaveraged FIR output pulse (solid) for an e-beam pulse (dotted) near the high end of the SEM current range. The wavelength is approximately 500 μm (0.6 THz), the grating period was 165 μm, and the accelerating potential 25 kV.

trends have emerged. The threshold currents increase with decreasing beam density. Threshold currents below 100 μA have been observed but typical values are in the 200–400 μA range. Since the threshold decreases with increasing beam current density but decreasing total current, it is assumed that limits set by the "surface resonator" characteristics of the grating are a dominant factor. A typical output power versus beam current curve is shown in Fig. 2. In the lower power linear regime the measured power, 100s of pW in the threshold region, are in accord with predictions [8] of the theory governing the spontaneous emission. Above threshold peak powers of 100s on nW are easily obtained and power levels in the μW range (at the detector) have been observed. At high levels the signal is observed directly at the output of the silicon composite bolometer. A typical pulse is shown in Fig. 3.

The intrinsic saturation limit for the system has not yet been established. If it is assumed that the basic constraints governing e-beams and gratings are similar to those which apply to devices such as Cherenkov free-electron lasers, ultimate electronic efficiencies in the 0.1–1.0% range can be expected from an optimized system. This would provide milliwatt level powers from an SEM driven device. A pulsed system may produce greater power. The present power levels are already useful for spectroscopic investigations and for driving heterodyne mixers with low-power requirements.

4. Tuning

The operating wavelength is determined by the expression

$$\lambda = \frac{\ell}{|n|}\left(\frac{1}{\beta} - \cos\theta\right) \qquad (2)$$

which is often referred to as the Smith–Purcell formula. In Eq. (2) ℓ is the grating period, $|n|$ is the order of the diffraction and θ is the angle of emission relative to the beam axis. The optical system in the present device collects only the normal emission. Wavelengths have been measured with an FIR grating spectrometer, polarizing and non-polarizing Michelson interferometers and cutoff filters. A compilation of the interferometer data is shown in Fig. 4.

Operation on orders other than the first is possible. By choosing the depth of the slot in order to reinforce the efficiency on a particular order, emission on that order will be dominant. A typical spectrum from the Martin–Puplett FTIR spectrometer is shown in Fig. 5 and the data from

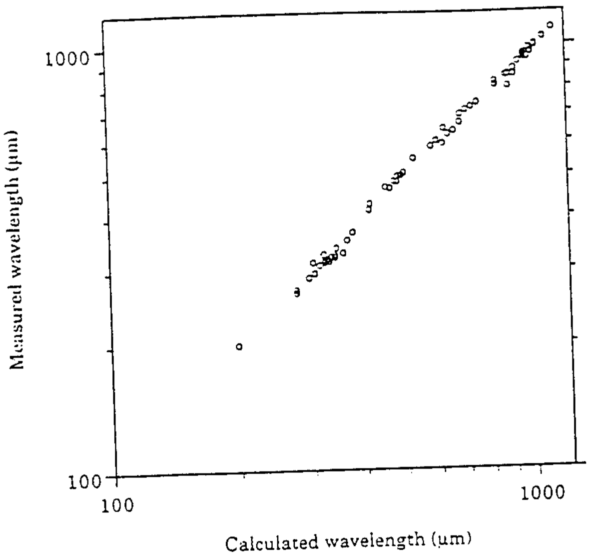

Fig. 4. Compilation of measured versus predicted wavelengths for emission in the normal direction.

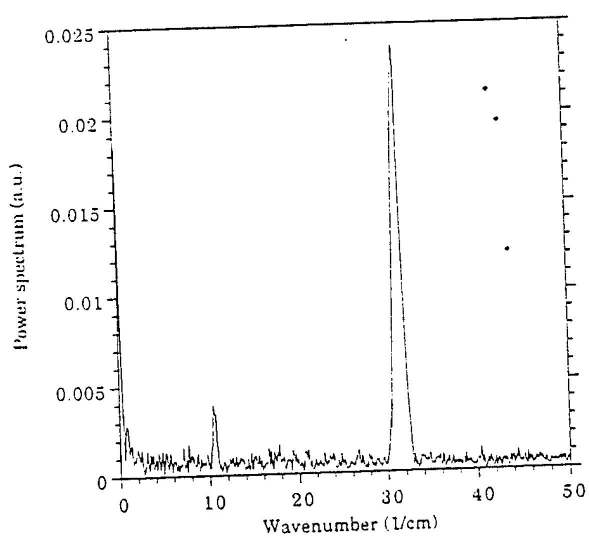

Fig. 5. A typical spectrum produced by the Martin–Puplett interferometer. The line width is comparable to the resolving power.

Fig. 4 is re-plotted as a function of the beam velocity in Fig. 6. Grouping in various orders is evident. Power generated on the higher order is comparable to the output that can be obtained from a grating which has the same period but which has been blazed for the first order.

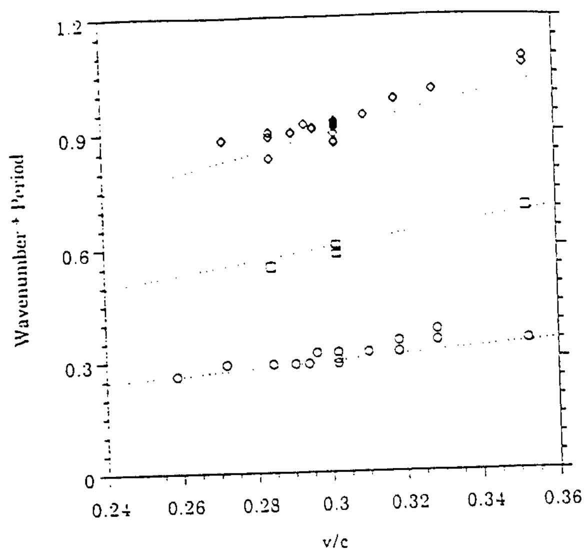

Fig. 6. Measured wave numbers in units of the grating period(s) versus relative beam velocity. Three orders are shown.

5. Conclusion

To date operation of the GCO has been extended down to 200 μm wavelength. Although the details of a theoretical picture are still unfolding, evidence suggests that device operation relies on a basic three-wave coupling. The high current density beam supports fast and slow (relative to the beam velocity) space charge waves. Coupling of these beam modes with a co-synchronous phase velocity space harmonic on the grating leads to a growing mode that is similar to a Cherenkov instability [9]. On the basis of this analogy, and presuming that e-beams representative of the electron optical state of the art are employed, extensions of GCO operation down into the 10s of μm wavelength range is a realistic expectation. With improved emittance this extension can be accomplished without a dramatic change in the beam current and voltage. The operational limit of this device is primarily a question of brightness. If pulsed field emitters or photo assisted field emission cathodes are adapted to GCO operation, and the beam quality maintained at higher (mildly relativistic) beam energies, then the wavelength would be further reduced and output power increased. Ultimately, when extending the range of any electron beam driven coherent source, beam quality and beam energy are key parameters. A fundamental conclusion that may be drawn from the present experiments is that substantial improvements in beam emittance and energy spread can reduce the need for high beam energy.

Acknowledgements

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References

[1] S.J. Smith, E.M. Purcell, Phys. Rev. 92 (1953) 1069.
[2] W.W. Salisbury, Super High Frequency Electromagnetic Wave Generator, US Patent 2,634,372, Applied – October 26, 1949, Awarded April 7, 1953.
[3] F. Rusin, G. Bogomolov, Proc. IEEE 720 (1969).
[4] K. Mizuno, S. Ono, Y. Shibato, IEEE Trans. Electron. Dev. ED- 20 (1973) 749.
[5] D. Wortmann, H. Dropkin, R. Leavitt, IEEE J. Quant. Electron. QE- 17 (1981) 1341.
[6] E. Price, J.E. Walsh, Appl. Phys. Lett. 61 (1992) 252.
[7] J. Urata, M. Goldstein, M.F. Kimmitt, A. Naumov, C. Platt, J.E. Walsh, Phys. Rev. Lett. 80 (1998) 516.
[8] M. Goldstein, J.E. Walsh, M.F. Kimmitt, J. Urata, C. Platt, Appl. Phys. Lett. 71 (1997) 452.
[9] E. Fisch, J.E. Walsh, Appl. Phys. Lett. 60 (1992) 1298.

A NEW FAR-INFRARED (FIR) SOURCE

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A new source of coherent, tunable, FIR radiation has been developed [1]. The essential features of the device are the beam in a scanning electron microscope (SEM) and a diffraction grating mounted in the e-beam focal region. The beam moving over the grating induces a surface current which in turn is responsible for the emission. When the beam current density is low, the total power generated is the result of an incoherent sum of the radiation produced by each electron in the beam. In this limit, the emission is in effect a shot noise process. If, however, the beam current density is high, as it may be in the SEM, the distributed feedback from the grating is sufficient to cause beam bunching and growth of a coherent mode of radiation. The grating is functioning as an open surface resonator and in recognition of this role the device has been termed a grating coupled oscillator (GCO).

A schematic diagram of the SEM is shown in Fig. 1. The beam is produced on a tungsten hairpin cathode and focussed and positioned over the grating with the aid of the microscopes internal electron optical elements. Beam voltages vary over a range extending from 20-40 kV and total current levels up to approximately 1 mA can be extracted. Coherent radiation can be obtained with beam diameter as large as 35 μm and in the present apparatus the lower limit to the beam diameter is about 20 μm. The coherent oscillation "turns on" when the beam current density reaches a point where the beam plasma frequency times the duration of an electron transit over the grating exceeds about 0.75. A typical power versus beam current curve is shown in Fig. 2.

The wavelength, λ, is determined by the so called Smith-Purcell relation [2]:

$$\lambda = \frac{\ell}{|n|}\left(\frac{1}{\beta} - \cos\theta\right) \tag{1}$$

In Eq. 1, ℓ represents the grating period, β the velocity of a beam electron relative to the speed of light, θ is the angle of emission relative to the direction of the beam, and $|n|$ is the order of diffraction. In the present device the emission is taken in the normal direction and diffraction orders up to $|n| = 3$ have been used effectively. The choice of dominant order is controlled by the grating profile.

To date, radiation over a wavelength band extending from 250 μm (1.2 THz) out to 1 mm (0.3 THz) has been obtained. Basic scaling relations developed to guide the design of the experiments indicate that coverage of the entire 10–1000 μm band should be possible.

A summary of these considerations and a review of the progress with GCO experiments will be presented.

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[1] J. Urata, M. Goldstein, M.F. Kimmitt, A. Naumov, C. Platt and J.E. Walsh, Phys. Rev. Lett. 80, 516 (1998).
[2] S.J. Smith and E.M. Purcell, Phys. Rev. 92, 1069 (1953).

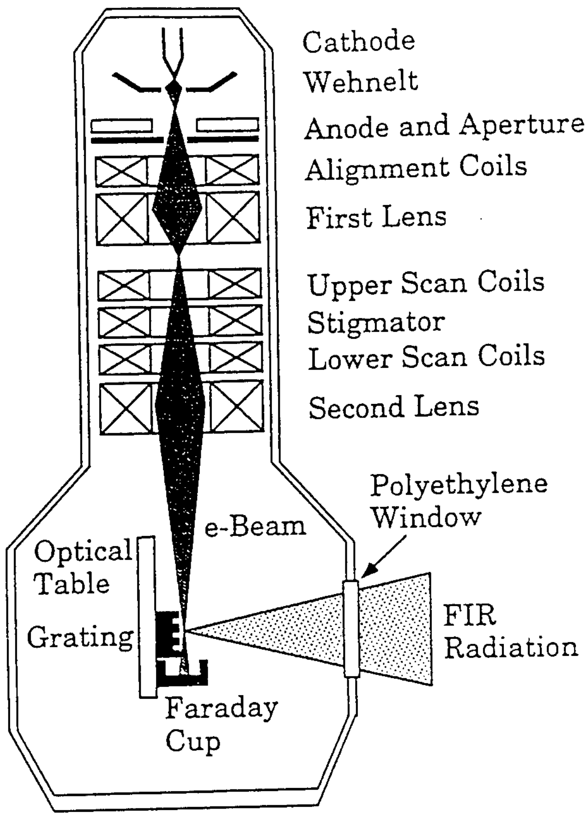

FIG. 1. Diagram of the SEM optical system.

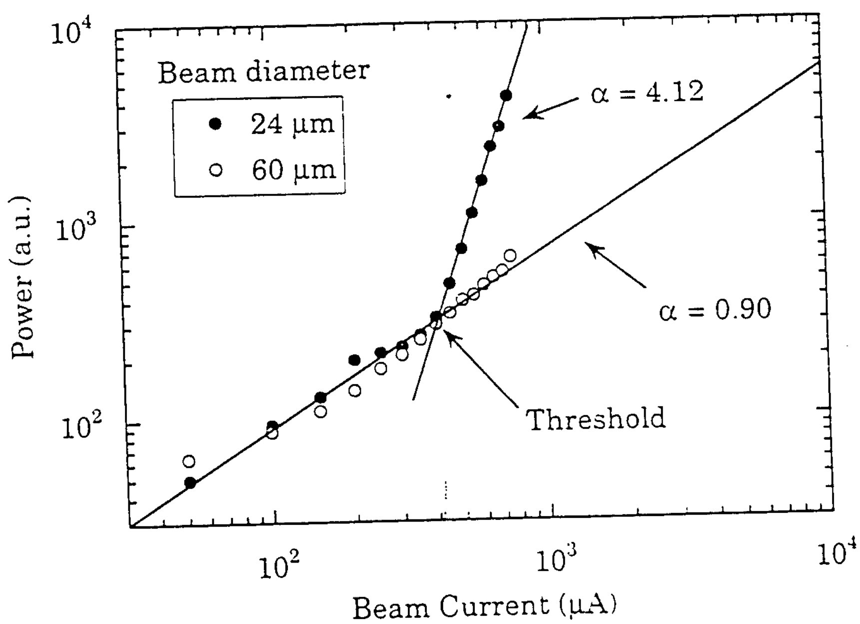

FIG. 2. GCO emission vs. electron beam current

3. Equipment Budget

1.	*Kimball Physics, Inc.* Electron Gun/Power Supply and Control Modules •311 Kimball Hill Road Wilton, N.H. (603) 878-1616; (Faye Bigarel)	55,600
2.	*Leybold, Inc.,* [2] D IOE TRIVAC E Pump @ $1,485/pump	2,970
3.	[2] RT 86251 TURBOVAC Pumps @ $7,277/pump •Woburn, MA; (617) 935-2022	14,554
4.	*Infrared Laboratories, Inc.* [2] Silicon Composite Bolometers @ $11,800/bolometer •1808 E. 17th Street, Tucson, AZ 85719 (602) 622-7074	23,600
5.	*EG & G Judson* [2] J10 D-M204 - R100U InSb Detectors @ $1,580/detector •221 Commerce Dr., Montgomeryville, PA 18936, (215) 362-6107	3,160
6.	*SPECAC, Inc.* [2 sets] Wire Grid Polarizer Pairs (25, 50 and 100 μm spacing) @ $12,495/set •301 Commerce Dr., Fairfield, CT 06430, (203) 366-5112	24,990
7.	*Hewlett Packard, Inc.* HP 54542A Digitizing Oscilloscope •H.P. Test and Measurement Sector, Santa Clara, CA (800) 452-4894	21,000
	Total Equipment cost	145,874
	Matching funds from Vermont Photonics, Inc.	25,000
	Total Requested from DoD:	120,874